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Direct imaging of isofrequency contours in all-dielectric optical metasurface

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Abstract. We study the properties of optical surface waves in all-dielectric anisotropic metasurface represented by an array of silicon slabs. We employ back focal plane microscope with solid immersion lens for direct imaging of isofrequency contours of surface waves of the metasurface to reveal both elliptic and hyperbolic-like regimes and reconstruct the dispersion curves for transverse and longitudinal directions.

1. Introduction

Metasurfaces are two-dimensional subwavelength-structured media that exhibit unusual optical properties and offer control over light propagation, reflection, and refraction unachievable in conventional media. In comparison with bulk metamaterials, metasurfaces are fully compatible with modern planar fabrication technology, preserving most of the functionalities of three-dimensional metamaterials.

Currently, most of the research devoted to metasurfaces is focused on their interaction with far field. This includes different phenomena, such as negative refraction, manipulation over wave front, phase and polarization of light etc. [1] Strongly localized surface states of metasurfaces deserve special interest, since dispersion law of such waves lays under the light line, so they propagate along the structure without leaking to the far field. It makes metasurfaces very promising for light manipulation in modern optoelectronic and alloptical circuits.

Direct experimental observation of unusual regimes of surface waves propagation in metasurfaces has been demonstrated in only a few papers. In particular, positive-to-negative refraction transition, diffractionless propagation and other effects were demonstrated in visible-frequency plasmonic metasurface. [2] Hyperbolic dispersion of surface waves wavefront was achieved by applying a nanoimaging technique to a 2D-material-based metasurface in midinfrared region. [3] Both the shape of the wavefronts and the propagation direction of surface waves are determined by group velocity $\mathbf{v}_g = \text{grad}_{\mathbf{k}}\omega$, which is aligned normal to the isofrequency contour. Therefore, a method for direct imaging of equal-frequency contours of surface waves would be an important tool for experimental studying of surface waves. On the other hand,



since plasmonic structures have high intrinsic losses, which imposes significant restrictions on the propagation length of localized modes, employment of the all-dielectric platform for engineering the dispersion of surface waves in the visible and near-infrared regions is preferable.

In our work, we propose all-dielectric metasurface with elliptic and hyperboliclike equal-frequency contours of surface waves in the visible to near-infrared spectral region. We resort to Back Focal Plane microscopy (BFP) with Solid Immersion Lens (SIL) in order to directly image the isofrequency contours. Spectral dependence of isofrequency contours obtained experimentally allows fast extraction of the dispersion law of surface waves in arbitrary direction.

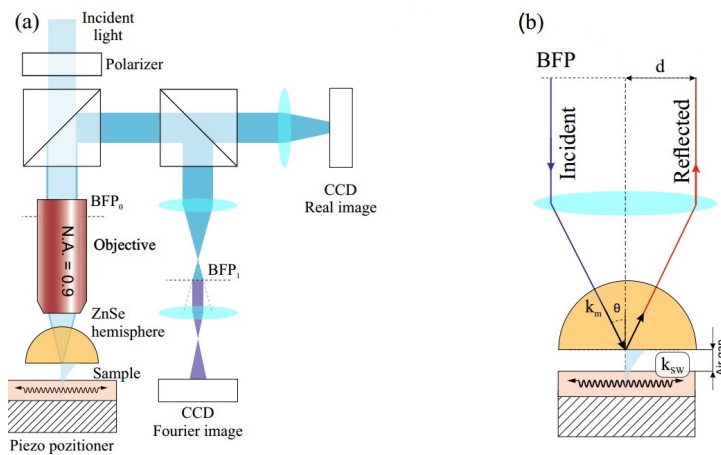


Figure 1. (a) Layout of the SIL-BFP setup.(b) Surface wave excitation and BFP imaging scheme. Surface waves are excited via frustrated total internal reflection in Otto geometry. In BFP of the objective distance d is proportional to k_{lat}/k_0 therefore reflectivity map in k -space is observed.

2. Methods

2.1. Experimental setup

Since the dispersion law of surface waves resides under the light line, special techniques are necessary to excite such states. For this purpose we apply Otto geometry with SIL based on ZnSe hemisphere (Fig.1 a). In the setup, the light passes through the objective and focuses on the flat surface of SIL. [4] At a certain angle and wavelength the lateral wave vector of the incident light coincides with the wave vector of surface wave which leads to its excitation via frustrated total internal reflection (Fig.1 b). The surface wave excitation is manifested as a dip in the reflectivity map for the respective k_x, k_y point in BFP of the objective. The full reflectivity map obtained in SIL-BFP setup for particular excitation wavelength thus illustrates the isofrequency contours of the surface waves excited in the sample. Maximum available angles and hence the wave vectors to be excited are determined by refractive index of SIL and numerical aperture of the objective: for ZnSe hemisphere refractive index is $n \approx 2.5$ and N.A. = 0.9 for our objective (Mitutoyo, M Plan Apo HR, 100, 0.9 NA). The excitation efficiency depends on the air gap which is controlled with high accuracy by piezopositioner.

2.2. Metasurface design and simulation method

We propose a simple design of all-dielectric anisotropic metasurface. (Fig 2 a,b) Metasurface parameters are chosen in such a way that the target isofrequency contour regimes (elliptic and hyperbolic-like) are observed in 650 — 1100 nm range. Due to anisotropy, the optical properties of surface waves depend on the polarization of incident light (transverse and parallel to bars).

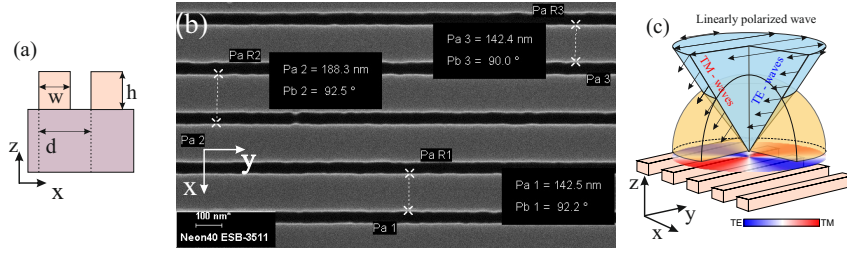


Figure 2. (a) Layout of all - dielectric the metasurface. We set $w = 140$ nm, $d = 190$ nm, $h = 75$ nm. Bar material is c - Si, substrate material is SiO_2 (b) SEM - image of metasurface. (c) Distribution of polarization in experiment. For our metasurface incident light polarization can be directed parallel or perpendicular to the bars.

To simulate the metasurface reflectivity in Otto geometry with different wavelength and polarization we used Fourier Modal Method (FMM). In particular, FMM makes it possible to obtain k - space reflectivity at BFP.

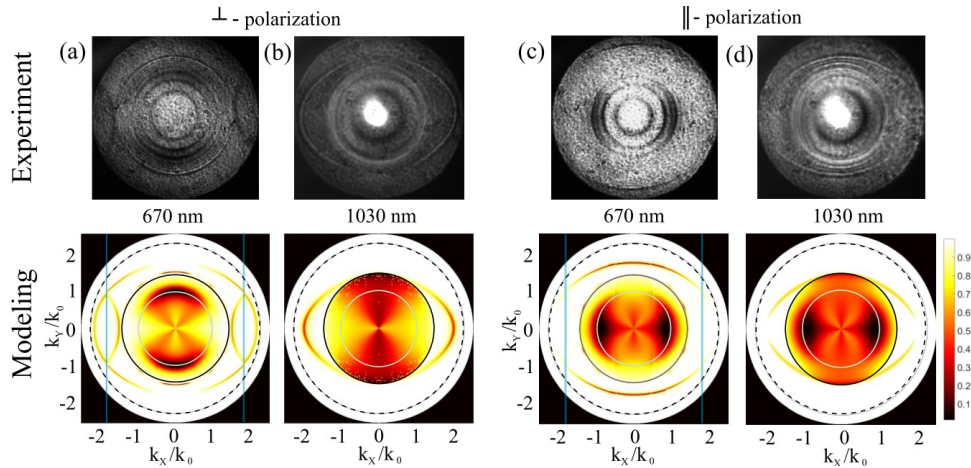


Figure 3. (a-d) Experimental and modeled images for metasurface reflectivity in BFP for transverse (a, b) and longitudinal (c, d) polarizations. In modeled images gray and black circles correspond to lateral wave vectors in free space and in substrate respectively, dashed curve meet the maximum wave vectors $n_{\text{ZnSe}} \cdot \text{N.A.}$. In (a, c) vertical blue lines means first Brillouin zone boundary. For transverse polarization hyperbolic - like (a) and elliptic (b) contours are observed. For longitudinal polarization (c, d) only elliptic curves are observed.

3. Results and discussion

The metasurface composed of an array of silicon slabs has been fabricated on a SOI substrate used focused ion beam milling.

Both in numerical simulations and experiment we observe that our metasurface can support substantially different regimes of surface wave depending on the wavelength and polarization of incident beam. For polarization parallel to the slabs, only the waves with elliptic isofrequency contours are excited, see Fig 3 (c, d). On the contrary, for transverse polarization we observe both hyperbolic-like and elliptic isofrequency contours of surface waves (Fig 3 a, b).

The origin of hyperbolic-like regime can be explained as follows. With the decrease of the wavelength elliptic curve crosses first Brillouin zone (BZ) boundary (blue vertical lines in Fig.

3 a, Modelling) and is translated according to the Bloch theorem from the second BZ to the first BZ forming hyperbolic-like contour characterized by negative curvature of the isofrequency contour.

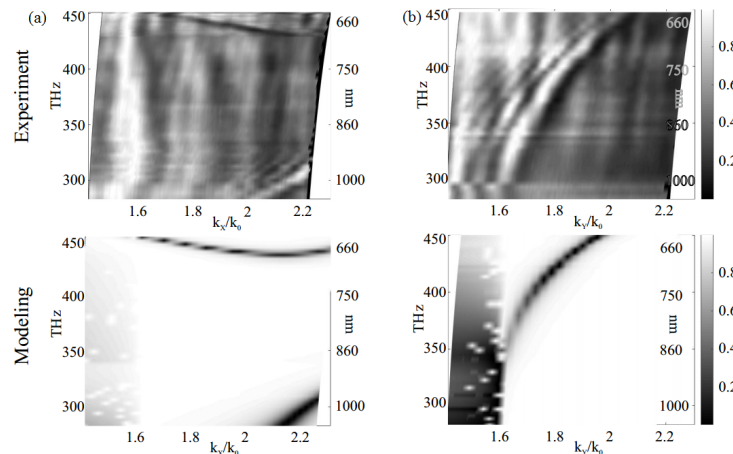


Figure 4. (a, b) Restored dispersion for metasurface. (a) In x direction wide band gap is observed. (b) In y direction ordinary dispersion curve is observed.

To determine wavelength range for all regimes and to reconstruct the dispersion curves for surface waves in longitudinal and transverse directions we measure the spectral dependence of SIL-BFP maps by tuning the excitation wavelength.

As a result, in longitudinal direction we see ordinary dispersion curve (Fig. 4 b, d), whilst in transverse direction we observe a wide band gap for surface waves (Fig. 4 a, c).

4. Conclusion

We have studied optical properties of surface waves supported by all-dielectric anisotropic metasurface represented by an array of silicon slabs. We resorted to BFP-SIL method to directly image isofrequency contours of surface waves in metasurface at different wavelengths and polarization of incident beam. We have shown that such a metasurface can support elliptic and hyperbolic-like regimes of isofrequency contours. The whole set of experimental data allows to reconstruct the dispersion curves of surface waves propagating in arbitrary direction.

5. Acknowledgements

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